Food Sec.
DOI 10.1007/s12571-014-0357-1

ORIGINAL PAPER

Taking stock of the genetically modified seed sector worldwide: market, stakeholders, and prices

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Received: 7 June 2013 / Accepted: 5 May 2014

Abstract The seed sector has become a subject of attention, debate, and even controversy with the development of genetically modified (GM) crops. However, this sector is generally rather poorly known. This paper aims to take stock of the economy of transgenic seeds in order to better understand the structure of this seed sector, its size, stakeholders, pricing, and major trends. The global market of the various types of seeds (saved, conventional, and transgenic) is first presented, as well as some aspects of their development, such as the significant consolidation in the past few decades. Next, the economic characteristics of the transgenic seed sector are analysed: actors, research and development expenditures, and the value of technology fees. In the final section, the cost of transgenic seeds is studied at the farm level, notably through the case of soybeans in the United States. The rise in transgenic seed prices over time is analysed as well as some repercussions of the growing trend toward the use of stacked traits. The conclusion highlights some issues related to the use of transgenic seeds from the point of view of seed and food security.

Keywords Seed industry · Seed market · Transgenic crop · Price · Concentration · Technology fee

Acronyms

GM	Genetically Modified
GMO	Genetically Modified Organism
GT	Glyphosate-Tolerant
HT	Herbicide-Tolerant
NGO	Non-Governmental Organization
R&D	Research and Development
SMEs	Small- and Medium-sized Enterprises
USDA	United States Department of Agriculture
USDA-ERS	USDA Economic Research Service
USDA-NASS	USDA National Agricultural Statistics Service

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Introduction

Today, agricultural issues have regained importance with the need to feed the growing world population while considering various issues: changes in patterns of food consumption and better food access, as well as environmental protection, natural resources and climate change. Agriculture must cope with new demands and challenges while maintaining biodiversity and avoiding a great increase in the area of cultivated land. Many scientists, politicians and citizens are now calling for a sustainable intensification of global agriculture, providing high yields and sufficient incomes for farmers and farm workers but without adverse environmental impacts. In this context, the seed sector has an important role to play (Science 2010). Plant breeding, in interaction with crop practices and production uses, influences the diversity of food, feed, fuel, and fibre obtained, as well as crops' characteristics, environmental impacts, and contribution toward food security. In addition, the techno-economic characteristics of seeds affect their accessibility, prices, and affordability, as well as some crop practices and nutritional aspects. It is therefore useful to better understand the seed sector, which is currently subject to debate and controversy, particularly with respect to the genetically modified (GM) seed sector.

Published online: 28 May 2014

Seeds play a key role in agriculture: a crop's success and many of its characteristics are highly dependent on their quality and properties. With the power to multiply — through photosynthesis, under favourable conditions, each kilogram sown may provide several dozen to a thousand kilograms of crops (Gallais 2011) — agriculture is a sector that literally creates biomass products. Plant breeding goes back almost as far as the origins of agriculture, approximately 10,000 years ago (Murphy 2007). The first farmers and especially their successors most likely sought to select the plants they found to be the most suitable and to use their seeds for the following crop. For thousands of years, seeds have been produced and saved by farmers in an empirical manner, traded on local markets, even stolen. This farm-based seed saving did not prevent the introduction of new species following intercontinental migrations and trade, particularly from the 15th century onward. In the 19th and 20th centuries, more scientific breeding methods began to develop, and plant breeding emerged as a profession. Seeds gradually became commodities, particularly with the development of hybrid varieties, seed standardisation, certification and control (OECD 2013), as well as the application of scientific knowledge in the field of biology and genetics. The rapid progress of modern biotechnology since the 1980s consolidated this trend. The world of seeds changed in parallel. In particular, the seed industry, previously made up of numerous small companies, became consolidated and partly absorbed by the crop protection industry. The transgenic seed sector is now especially concentrated.

The use of genetic engineering in plant breeding has led to great controversy with respect to the benefits and risks of GMOs (FAO 2004; Weasel 2008). The GMO debate has drawn attention to the plant breeding sector and particularly the GM seed industry. A number of non-governmental organisations (NGOs), media, citizens, elected officials and some farmers' associations have become highly critical of the seed industry, notably the largest seed companies. They have denounced the trend toward concentration and the potential dependence of human food on a few companies to feed the world's population; they have also been critical of increasing GM seed prices (ETC 2005; Hubbard 2009; Shiva et al. 2011). These criticisms have found great resonance in the media and on the Internet. This distrust has contributed to a growing divide concerning the path agriculture should take in the coming years and decades. Some argue for the need to accelerate use of modern technologies, such as biotechnology and genomics, whereas others are calling for the use of grass roots technologies in order to better ensure food security for all. Many people see biotech crops as an imperative for achieving food security and sustainable agriculture (Fedoroff et al. 2010; Jones 2011; Bennett et al. 2013; Bennett and Jennings 2013), while others see them as a false solution put forward for the benefit of a handful of companies (Altieri and Nicholls 2005; Spring 2011; Jacobsen et al. 2013).

Considering these many stakes, it appears useful to look more closely at the rapidly evolving seed sector. While many papers on the Internet and in the media deal with this sector, particularly the transgenic sector and its leading companies, there is often a lack of precise appraisals and analyses. In addition, although a very abundant literature addresses GM crops, few scientific papers focus on the GM seed sector itself. The main objectives of this text are thus (i) to assemble the most accurate and comprehensive data available on the contemporary GM seed industry and its importance within the seed sector as a whole; (ii) to contribute to a better assessment of some specific economic issues within the sector, including its structure, concentration, seed costs to farmers, and how these costs have changed over time; and (iii) to better understand the implications of these recent and ongoing trends. As the GM seed sector cannot be studied in isolation, but only in relation to the overall seed sector of which it is a part, this article will first provide an overview of the latter. Thus, the first part will assess the global seed market, its structure and concentration trends, and its economic importance in the food chain. Then, the GM seed actors and markets will be analysed, as well as the value of technology fees and the research and development (R&D) investments of the principal companies involved. The last part will address the costs and returns of transgenic seeds compared to conventional seeds at the farm level, using the case of soybean, the most widely cultivated transgenic crop. It will also address the evolution of seed prices over time, notably with the trend of trait stacking. This paper will not address issues of patents or farmers' rights to save seeds, which have already generated a very abundant literature (Tansey and Rajotte 2008; Blakeney 2009).

This article is based on an extensive search for and analysis of accurate, precise, and up-to-date information on the seed sector, including papers by seed experts and analysts, company reports and presentations for shareholders, professional and NGO appraisals and conference presentations, in addition to the scientific literature on the subject, as well as a monitoring of the major developments in this sector. Company reports include annual reports, financial statements and sales figures by sector, as well as R&D investments and new products in the pipeline. Professional appraisals include data from national and international seed associations. Compiling these statistics on the global or sectoral seed market is a daunting task because of the paucity of readily available, accurate data and because of discrepancies among the data that are available, as explained below. In the final section of the paper, examining conventional and transgenic seed prices and production costs for US soybeans over the past few decades, we made particular use of data from the USDA National Agricultural Statistics Service (USDA-NASS).

The global seed market: composition, size and restructuring

The main types of seeds: a difficult appraisal

It is first necessary to briefly examine the global seed sector, which encompasses both the commercial seed market and farmer-saved seeds. However, the appraisal of farmer-saved seeds is particularly difficult. In the early 1990s, a Rabobank report (1994) valued this "market" at 15 billion USD; in 2002, Convent estimated it at 13 billion USD (Convent 2003, quoted by Graziano Ceddia and Rodríguez Cerezo 2008); in 2006, the estimates varied from 6 to 15 billion USD (Bruins 2010; Fuglie et al. 2011). This informal seed sector comprises farmer-saved seeds as well as seeds exchanged in local markets. The former are especially present in developing countries, but are also present in developed countries for species such as wheat, for which few hybrid varieties have been commercialised. In the US in 2009, for example, approximately 59 % of winter wheat was sown using saved seed, according to the Agricultural Resource Management Survey (USDA-ERS 2013c). In France, for the period 1981 to 2012, saved seed represented from 38 % to 51 % of the total crop planted, depending on the year (45 % on average), without any marked downward trend (GNIS 1982–2013).

Valuations of the commercial seed market also vary (Then and Tippe 2009; Schenkelaars et al. 2011; Fuglie et al. 2011; Joly 2012; Moeller and Stannard 2013). Indeed, the majority of estimates are made by consulting firms specialising in this domain. Many focus on their clients' market, which is to say that of the major seed companies. For example, in 2011, some consulting firms assessed the global seed market to be worth approximately 34.5 billion USD (McDougall 2012) or 37 billion USD (Context Network 2012). However, other estimates, such as those by the International Seed Federation (ISF), also consider small and medium-size enterprises (SMEs) in each country, as well as the segmentation of the seed sector by species (grains, oilseeds, vegetables, forage, fruits, and horticulture). In 2011, the ISF assessed the global commercial seed market to be worth 45 billion USD (ISF 2012). This estimate is based on data on the domestic seed market in each country as reported by national seed associations, with some limited extrapolations where data are missing (McNabb 2013).

With regard to the total seed market, there are also certain variations in the estimates since the available studies don't always cover the same extent of the sector. In addition, companies' sales values are necessarily approximate due to significant fluctuations in exchange rates between different currencies, mismatches between the financial years of different firms, and the fact that they cover several product lines. Here, the ISF values were retained for the global seed market, as they are more inclusive and thus more accurate, taking into account more than 7,500 seed companies worldwide. According to the estimates of ISF, the world seed "market", including the informal sector, may have an approximate value of 55 billion USD for 2011. If the informal sector is excluded, global commercial sales may have been approximately 47 billion USD in 2012 (McNabb 2013). This commercial seed sector can be divided into two parts: conventional seeds and GM seeds (Table 1).

As there are very few readily available data sources on the value of the commercial seed market (certain data only being available in extremely expensive market research reports), the majority of papers citing figures on this topic use data from an NGO known as the ETC group (Action Group on Erosion, Technology and Concentration). Over the years the ETC group has published many vivid papers on the seed sector, highlighting the consolidation and providing an assessment of the seed market, including the turnover of the main companies. However, the ETC group has generally relied on the estimates of market research firms such as Context Network or Phillips McDougall (ETC 2005, 2008, 2011, 2013a, b). Because these assessments do not consider the seed sales of the SMEs, they lead to an underestimation of the value of the global commercial seed market and hence give more weight to the large companies and to GM seeds within the overall global market. For example, several detailed evaluations of seed industry concentration made in 2009 concluded that the top ten seed companies represented approximately 48 % of the global commercial market (Then and Tippe 2009; Fuglie et al. 2011; Schenkelaars et al. 2011); but the most quoted figures on the Internet — based on ETC reports — were that ten seed companies controlled over two-thirds of global seed sales (ETC 2011). Moreover, because of the high growth rate of the seed market over the past few years, some recent market research reports have provided higher assessments of its 2013 value: 48 billion USD (Research and Markets 2013) and even 50 billion USD (Halsall 2013). This confirms the ISF values retained here.

Many comments circulating in the media and on the Internet emphasize the economic weight of the major seed companies, described as "global giants". However, these figures are generally considered in isolation. To put these figures in perspective, it is useful to compare the economic size of the seed industry to that of other sectors. The value of the commercial seed market in 2012 (approximately 47 billion USD), for example, can be compared to that of other sectors in the agro-food chain. According to Marketline (2013), an approximate assessment of the global food and beverages retail market was 5.98 trillion USD in 2012 and 4.8 trillion USD in 2009. The value of the seed sector is thus less than 1 % that of the global food retail market. Because total markets are difficult to estimate, Fig. 1 shows the global sales values of the top ten companies for four sectors: seeds, agrochemicals, food processing, and food retail. The seed industry weighs very

Table 1 Global seed market in 2008 and 2011 according to the types of seeds: approximate estimates (billion USD and %) (from ISF 2012; McNabb 2013; James 2013; Bruins 2013; the sources used are discussed in the text)

	2008		2012	
Types of seeds:	(USD billion)	In % commercial	(USD billion)	In % commercial
- Conventional seeds	31	77.5	32	68
- GM seeds	9	22.5	15	32
- Farmers' saved seeds (approx. estimate)	*14*	-	*10–12?*	-
TOTAL	54	-	57–59?	-
Of which total commercial:	40	100	47	100

little in economic terms within the agro-food chain, as some authors have already noted (von Braun 2008). The global ranking of companies also shows that the leading companies in the agro-food chain are those of the processing and retailing sectors, not those of the seed sector (Forbes 2012–2013). For instance, if agro-food companies are ranked by their global sales, the largest companies are the leading food retailers (such as WalMart, Carrefour, Tesco), large food and drink processors (Nestlé, Unilever, etc.), and giant wholesalers and food processors (such as Archer Daniels Midland and Bunge). In 2012 for example, PepsiCo's and Coca-Cola's turnovers were higher than the total value of the global commercial seed market. Major chemical companies (Bayer, DuPont, Dow, etc.) also make the majority of their sales in drugs and other chemicals, not in seeds or agrochemicals. According to a ranking based on sales, Monsanto, the world's leading seed company, was ranked 686th in 2012 and 732nd in 2011, among all companies worldwide (Forbes 2012–2013). Even though the economic influence of a market sector cannot be assessed solely by its economic size, it is useful to put the latter into perspective.

The small economic weight of the seed sector within the agro-food chain can be regarded as obvious from an economic point of view: in a supply chain, sales are higher in downstream segments than in upstream segments, as value is added along the chain. Nevertheless, the relatively small size of the seed sector should be underlined as it runs contrary to popular opinion. As they are located at the entry point of the food chain, the influence of agricultural input industries is often emphasized, while the power of the downstream sector demands is less often considered. In the agro-food chain, the major economic player may be food retail, as this sector is also highly concentrated and wields great power due to the existence of purchasing pools, which create a bottleneck for access to downstream markets. It also influences the entire agro-food chain through its requirements and the pressure it exerts on agricultural prices, as well as on food consumption patterns (Bonny 2006; IAASTD 2008; von Braun and Diaz 2008).

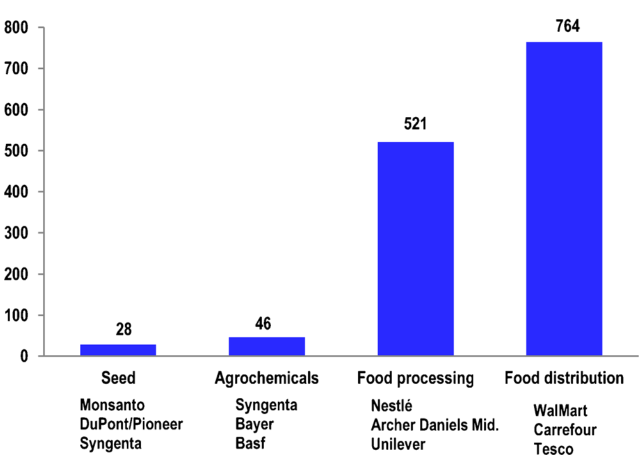

Fig. 1 Global sales of the top ten companies in four sectors: seed, agrochemicals, food processing, and food retailing (in 2012, billion USD). The names of the 3 major groups are indicated for each sector (from Forbes 2013; Supermarket News 2013)

Significant consolidation

The seed sector has been marked by significant restructuring and a merger-acquisition trend in recent decades (Fernandez-Cornejo 2004; UNCTAD 2006; Howard 2009; Schenkelaars et al. 2011; Fuglie et al. 2011; Mammana 2014). This occurred in several phases: (i) pesticide companies invested heavily in biotechnology, either by creating internal research laboratories or acquiring SMEs specialised in agricultural biotechnology research, (ii) agrochemical firms made acquisitions in the seed sector; (iii) agrochemical players severed the link with the pharmaceutical sector which many held at the end of the 1990s (Lemarié 2003). The outcome was, in the early 2000s, the creation of six large groups involved in both the agrochemical and seed sectors and known as "the Big Six" (Fig. 2). Since then, they have remained the leaders in the crop protection market while increasingly investing in seed and plant biotechnology. Several factors explain why the largest agrochemical groups have entered the seed and biotech sector, including the expectations of better returns, given that the costs of placing a new active chemical ingredient on the market have increased. In 2009, this was estimated to be higher (256 million USD) than the cost of launching a new plant biotech trait (136 million USD), according to company surveys conducted by Phillips McDougall (2011, 2013). Thus the three largest seed companies in the world are now agrochemical groups that have entered the seed sector (Fig. 3).

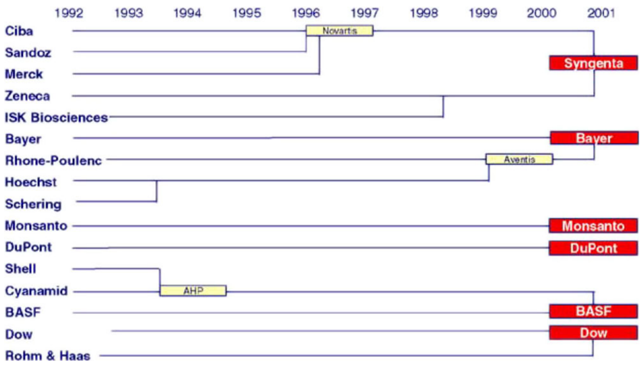

Fig. 2 Consolidation in the agrochemical industry in the 1990s: a simplified view. Reprinted from *Computers and Chemical Engineering,* 29(1), Cordiner, J.L., Challenges for the PSE community in formulations, pp. 83–92. Copyright (2004) with permission from Elsevier (2013)

Seed industry concentration increased over recent decades with the top five companies commanding a larger share of the total market (Table 2) (Fig. 4) (Black et al. 2006; Bruins 2008, 2010; Le Buanec 2009; Ragonnaud 2013).

The "Big Six" companies currently have varying amounts of global seed sales (Fig. 5). They are particularly notable in the case of Monsanto and DuPont-Pioneer, but lower for the other companies coming from the crop protection sector, i.e., Syngenta, Bayer, Dow, and BASF. The latter companies still predominantly sell agrochemicals and, except for Syngenta, also have substantial production in other areas of chemistry. Monsanto is highly specialised in plant biotechnology: although it sells glyphosate in a variety of forms, the proportion of glyphosate in its total sales has decreased gradually following the expiration of the patent for this herbicide. Thus, the groups involved in plant biotechnology have different profiles depending on their level of specialisation in this domain.

GM seeds: technology fees, market and actors

The worldwide transgenic seed market has grown rapidly since 1996 (Fig. 6), and GM crops have developed

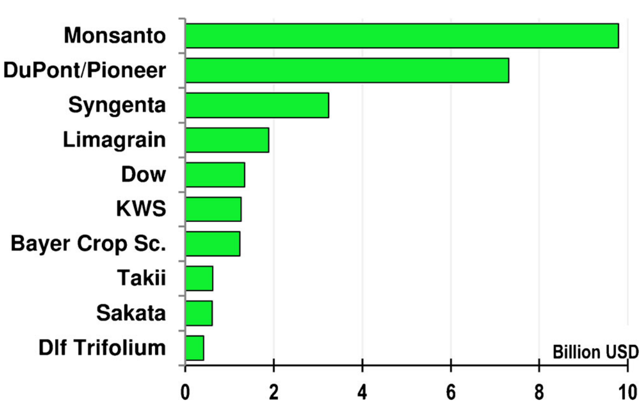

Fig. 3 Major seed groups in the world in 2012 (seed sales in billion USD) (from company annual reports, sales reports and public filings)

particularly in America (Table 3). With a total value of 15.6 billion USD in 2013, according to ISAAA estimates (James 2013), the GM seed market is already high in overall seed sales: its proportion in commercial seed sales rose from 9 % in 2001 to 21 % in 2007, and to almost one-third in 2013. However, the GM seed market is approximately ten times lower than the market for pharmaceutical and health products from biotechnology, which was valued in 2013 at approximately 165 billion USD (BioPlan Associates 2013). Today the main applications of biotechnology are in the health sector. In 2012, GM seed sales represented approximately 31.5 % of the global commercial seed market. Meanwhile, GM crops represented only 11 % of cultivated land. GM seeds can be estimated to be two or three times more expensive than conventional seeds.

Actors and technology fees in the GM seed sector

For GM seeds, in addition to the cost of the seeds and their treatments, farmers must pay a technology fee to the holder of the patent(s) who discovered and implemented the means for transferring a new trait(s) into the crop. Technology fees are royalties due to an inventor, the owner of a patent for a discovery, in exchange for the right to use it through a license. They are intended to reward the R&D efforts of the companies involved. Indeed, if crop varieties may be saved and replanted without any financial rewards to plant breeders, private companies have no incentive to invest in plant breeding, since the result of almost ten years of R&D may be copied and multiplied once the new variety is put on the market (Arrow 1962). The financial gains achieved in the first year, when farmers buy the new variety for the first time, is insufficient if farmers save the seeds in following years without any return to the breeder. This has led to the implementation of two options: either public plant breeding or private breeding rewarded by breeder rights (or patents). For GM seeds, farmers generally pay technology fees simultaneously with the seed purchase. The various seed companies transfer these fees to the agri-input companies (e.g. Monsanto), which have granted licenses for the inclusion of their patented traits within the various end-user varieties (Shi and Chavas 2011).

When the seeds are transgenic, the seed industry includes several types of actors: (i) the "trait providers", who grant licenses for the new GM traits they have obtained; (ii) the large companies, which use these new traits as well as those resulting from their own research, placing them into seeds that they develop and sell; and finally (iii) the other seed companies that develop many different varieties adapted to different climatic and soil conditions, inserting into them new traits for which they have been granted licenses. It is thus necessary to distinguish trait ownership from seed ownership. For example, in the US, although an overwhelming majority of the GM seeds in use have carried traits from Monsanto in the past few

Table 2 Ranking of the top ten seed companies in 1985, 1996, 2009, and 2012 (company sales in million USD) (from James 1997; Black et al. 2006; Schenkelaars et al. 2011; Fuglie et al. 2011; von Broock and Bruins 2012; and company annual reports)

The companies' sales values are necessarily approximate due to significant fluctuations in exchange rates between different currencies, mismatches between the financial years of different firms, and the fact that they cover several product lines

1985	Sales	1996	Sales	2009	Sales	2012	Sales
Pioneer	735	Pioneer	1,500	Monsanto	7,297	Monsanto	9,789
Sandoz	290	Novartis	900	DuPont Pioneer	4,806	DuPont	7,311
Dekalb	201	Limagrain	650	Syngenta	2,564	Syngenta	3,237
Upjohn Asgrow	200	Advanta	460	Limagrain	1,370	Limagrain	1,884
Limagrain	180	Seminis	375	KWS	996	Dow	1,340
Shell Nickerson	175	Takii	320	Bayer CropSc.	699	KWS	1,262
Takii	175	Sakata	300	Dow	633	Bayer Crop Sc	1,231
Ciba	152	KWS	255	Sakata	485	Takii	0,621
VanderHave	150	Dekalb	250	DLF Trifolium	391	Sakata	0,608
CACBA	130	Cargill	250	Takii	347	DLF Trifolium	0,415
Sales of the top ten companies in % of global seed sales	12 %		18 %		47 %		59 %

years, a large part of these seeds were commercialised by other seed companies. In 2011, when GM crops had a prevailing share portion of Monsanto GM traits, 88 % of US corn acreage was GM, while Monsanto controlled approximately 33 % of the US corn seed market through direct sales. For soybeans, where 94 % of the acreage was GM, the respective share of Monsanto's direct seed sales was approximately 24 % (Schafer 2012), or 34 % if its subsidiary American Seed Inc. is included.

Since 1996, when the commercialisation of GM crops began, the value of technology fees has varied over time and according to the new traits introduced (Fuglie et al. 2011). This variation depends, in particular, on the number of traits (some varieties incorporate several stacked traits), their agro-economic interest, the state of competition and the level of advancement of the technique. A number of surveys were conducted in the mi-2000s on the size of the technology fees within the total price of several GM seeds (Smolders 2005; Freese 2007; Bruins 2008; Le Buanec 2008, 2009; Moss 2013). In the total value of the seed, technology fees may have constituted 23 % to 68 %, and the genetic contents 26 to 62 % (Table 4). In addition, particularly with gene stacking, technology fees have increased in the last few years, and this trend is forecast by the seed market analysts to continue (Research and Markets 2013). With respect to the global value of technology fees, a few companies provide some assessments: overall in 2011, in the global market for GM seeds of 13.2 billion USD, they represented 4.1 billion USD, i.e. 31 %, and approximately the same proportion in 2010 (Devgen 2012).

Notwithstanding, Kalaitzandonakes et al. (2010, pp. 25–26), who compared the revenue stream from mark-ups and premiums of biotech traits to R&D expenditures and estimated that "*until 2005, ten years into the commercial phase of agricultural biotechnology, revenues from mark-ups and premiums from the US corn and soybean seed markets were less than 80 % of R&D expenditures*". However, technology fees are high compared to the total value of GM seeds. As Hubbard (2009, p. 16) writes, "*the biotechnology industry tends to overvalue genetically engineered traits and undervalue the germplasm*". High-quality germplasm, as well as regionally specific varieties tailored to different climatic and soil

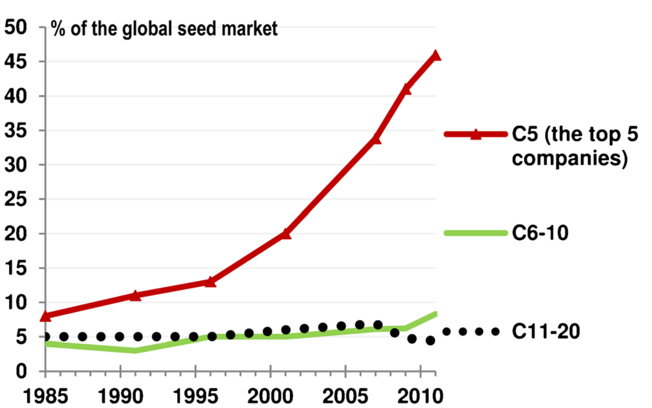

Fig. 4 The concentration of the seed sector is reflected in the growth of the market share of the top 5 companies. *Cn* is the share of the total sales sold by the company ranked n^{th} (adapted from le Buanec 2008; Bruins 2010, 2013)

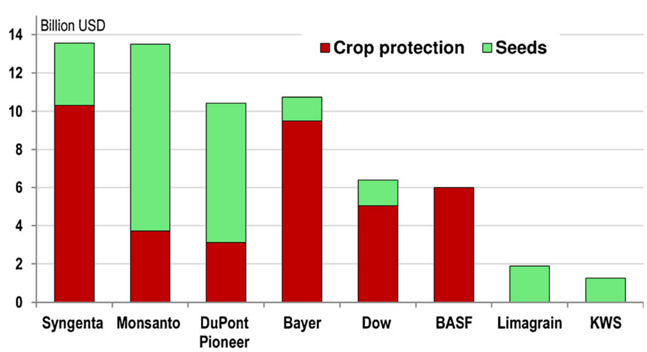

Fig. 5 Seed and crop protection sales by the main companies involved in GM seeds in 2012 (billion USD) (from company annual reports)

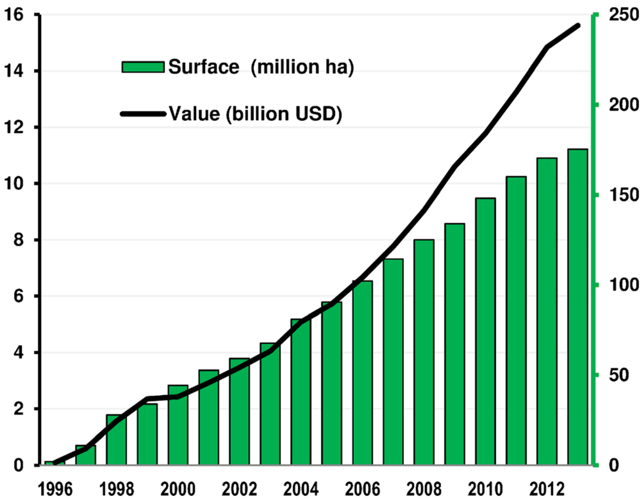

Fig. 6 The total sales of GM seeds worldwide and the total area of GM crops, 1996 to 2013 (billion USD at the left scale, million ha at the right scale) (from James 2013)

conditions, are by far the most important characteristics of seeds. Biotech traits only add one or a few additional characteristics, while the agricultural value of the seeds depends on the entire genotype.

Who invests in GM seeds, and to what extent?

Research and development (R&D) investments increased in plant breeding when applications of scientific and technological advances in genetics, life sciences, biotechnology, and genomics became increasingly common. For example, in the US, seed and biotechnology, which were a minor sector in private research expenditures in 1979, have become, three decades later, dominant within private agricultural input research (Fuglie et al. 2012a; Fuglie and Toole 2014). If the total costs from discovery and development through regulatory approval are considered, GM seeds are costly to develop (McDougall 2011). In addition, the time required to commercially launch a new product is long: 13.1 years on average in 2008–2012. High R&D spending seems to be a significant factor which has contributed to the concentration of the seed sector (Schenkelaars et al. 2011).

The largest of the agrochemical and seed groups have invested in GM seeds while the share of public R&D has decreased. The R&D expenditures of the companies involved are large as well as highly concentrated (van Beuzekom and Arundel 2009). Eight main groups are involved: Monsanto (US), DuPont-Pioneer (US), Syngenta (Switzerland), BASF (Germany), Dow (US), Bayer (Germany), Limagrain (France), and KWS (Germany) (Fuglie et al. 2011; McDougall 2012). In addition, small biotech firms, start-ups (trait or technology providers), international research centres linked to the Consultative Group on International Agricultural Research *(*CGIAR*)*, and the public research sector invest in R&D in this area, but to a lesser extent. The agrochemical groups other than Monsanto invest in both the seed sector and crop protection to varying extents. Monsanto is distinguished by its high R&D expenditures on seeds, far higher than its competitors, whereas few of its R&D expenses relate to crop protection (McDougall 2012). Monsanto's competitors generally have more diversified R&D investments distributed among several sectors: agrochemicals, pharmaceuticals, and general chemistry. However, Monsanto has recently begun to get involved in other sectors such as precision agriculture and biologicals. For about a decade, the R&D expenditures of the "Big Six" have evolved in a differentiated way, with a sustained rhythm in the seed sector and slower growth in agrochemicals. Since 2009, Big Six R&D investments in agrochemicals have been overtaken by those in seeds (Fig. 7). This reflects the companies' increasing involvement in the seed sector and, in turn, the current and future importance these companies grant biotechnology.

The prevalence of the private sector in agricultural biotech R&D and the prominent position of Monsanto stand out more markedly when one examines the firms conducting GMO field trials. For the period 1987–2010, for the main countries and regions involved (US, EU, Argentina, India, Australia), Schenkelaars et al. (2011) have tallied the number of applications for GM field trials by the type of organisation, including

Table 3 Distribution of GM crop acreage in the world in 2013 (area in Million ha) (from James 2013)

By COUNTRY	Area	% total	By CROP	Area	% total	By GM TRAIT	Area	% total	% total incl. stacked traits
USA	70.1	40	Soybean	84.5	48	Herbicide tolerance (HT)	99.4	57	HT: 84
Brazil	40.3	23	Corn	57.4	33	Herbicide tolerance (HT) & Insect resistance (IR)	47.1	27	
Argentina	24.4	14	Cotton	23.9	14				IR: 43
India	11.0	6	Canola	8.2	5	Insect resistance (IR)	28.8	16	
Canada	10.8	6	Alfalfa	0.8	<1	Virus resistance or other	<1	<1	
China	4.2	2	Sugar beet	0.5	<1				
Paraguay	3.6	2	Other (squash, papaya)	<0.1	<1				
South Africa	2.9	2							
TOTAL	175.2	100	TOTAL	175.2	100	TOTAL	175.2	100	

Table 4 Technology fees, seed treatments and seed intrinsic genetic value in percent of the total unit price of some GM seeds. Some examples, according to several GM seeds and traits in different countries, in the mid 2000s (adapted from Smolders 2005; Bruins 2008; Le Buanec 2008)

	Percentage in the total unit price of the seed of:		
GM seeds:	Intrinsic genetic value	Seed treatments	Tech fees
Corn (insect resistant, 1st generation)	62	15	23
Corn (herbicide tolerant (HT), 1st generation)	58	17	25
Corn double stack (HT+insect resistant)	52	15	33
Corn double stack (HT+insect resistant)	50	12	38
Corn triple stack (HT+double insect resistant)	40	9	51
Sugar beet	38	21	40
Soybean (HT)	47	13	41
Cotton Bt (insect resistant)	34	11	55
Cotton double stack	26	6	68

public research: Monsanto accounted for 41 %, the "Big Six" for 66 %, and the public sector for 19 %. In the US, where a substantial percentage of these trials have taken place, Monsanto applied for almost half of all GM field trial applications made by private companies in the 2000s (OECD 2009; Arundel and Sawaya 2009). Within GM crop approvals, the dominance of the Big Six is even higher (Fuglie et al. 2012b).

Which countries invest the most in plant biotechnology? While it would be interesting to compare R&D expenses across countries, doing so is difficult as biotechnology R&D spending is predominantly invested in the health sector, not in plant biotech, and the share of the latter is difficult to estimate (OECD 2009). Another challenge in assessing R&D spending in GM seeds is that GM plant breeding requires conventional breeding, other biotechnological techniques, and genomics in addition to genetic engineering. For these reasons, appraisals of R&D expenses are often made for the seed sector as a whole. Some assessments of global R&D expenditures for crop biotechnology, conducted for the end of the 1990s and for 2001, have shown the dominance of industrialized countries within this field (James 2003; Pingali and Raney 2005). In the last few years, however, China, India, and Brazil have substantially increased their R&D spending (Beintema et al. 2012).

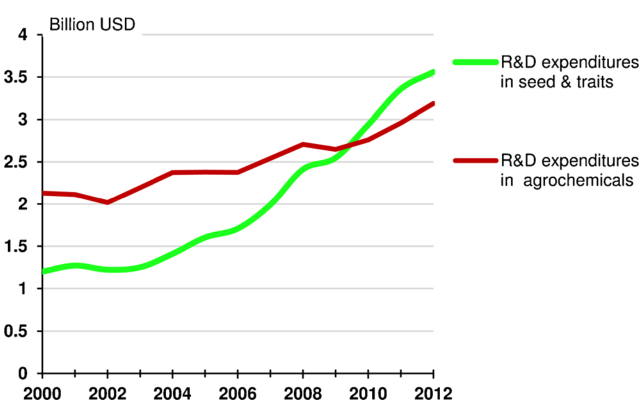

Fig. 7 R&D expenditures for seeds/biotechnology and crop protection by the six largest agrochemical groups, 2000–2012 (from Jones 2012)

It would also be significant to compare public and private R&D expenses in plant biotechnology. Admittedly, they are difficult to compare, as private R&D is currently focused more on the downstream sector of plant breeding while public R&D focuses on the upstream sector: public research tends to work on fundamental knowledge of the genome, genomics and its applications, as well as on genetic resources (King et al. 2012; Fuglie and Toole 2014). The case of the US shows that, from the late 1980s onwards, the majority of research in plant breeding has been financed by the private sector (Fernandez-Cornejo 2004; Day-Rubenstein 2010; Schenkelaars et al. 2011; Fuglie and Toole 2014). Data differentiating between public and private R&D expenses in plant biotechnology are rare for recent years, however. Pingali and Raney (2005) estimated that private R&D expenses represented 57 % of global R&D expenses for crop biotechnology at the end of the 1990s, whereas James (2003) has assessed this share to be 70 % in 2001. Currently, there are also substantial public investments in China, India, and Brazil; but in developed countries investments in green biotechnology are above all private (Huang et al. 2005; Alston et al. 2009; Beinteima and Elliot 2009).

Despite concerns, the area of GM varieties continue to grow

The concentration of the GM seed sector worries many stakeholders: some sector professionals, some farmers' associations, as well as anti-globalisation and environmentalist organisations and some citizens' associations (ETC 2005, 2008, 2011; Hubbard 2009; Then and Tippe 2009; Shiva et al. 2012; Mammana 2014). These groups fear food dependency on a small number of firms: "*if they control seed, they control food*", as Vandana Shiva states in the film *"The World According to Monsanto"*. The repercussions of seed industry concentration are seen as extensive: "*With control of seeds and agricultural research held in fewer hands, the world's* *food supply is increasingly vulnerable to the whims of market manoeuvres. Corporations make decisions to support the bottom line and increase shareholder returns — not to insure food security. Ultimately, seed industry oligopoly also means fewer choices for farmers.*" (ETC 2005, p. 1). Concern over the concentration of the seed industry also exists among smaller seed companies and other organisations, such as those advocating for market freedom and anti-trust regulations (OCM 2008; CESE 2009; Domina and Taylor 2009; Moss 2013). These concerns have been reinforced by the increase in GM seed prices (Hubbard 2009; Moschini 2010) and by the fear of a decrease in the supply of non-GM seeds for some crops, as well as by worries about the licensing agreements made between Monsanto and other smaller seed companies using Monsanto's traits in their own strains. However, the main grower organisations, such as the ASA (American Soybean Association) and the NCGA (National Corn Growers Association) in the US, continue to actively promote agricultural biotechnology.

Despite all these concerns and the controversy over GMOs, the spread of GM crops has not diminished in the past 15 years, even if their growth rate was lower in 2013. According to ISAAA figures (James 2013), global GM crop area has increased each year since 1996, with the exception of Europe in certain years (although the total GM crop area is very small in Europe). Nevertheless, the development of GM crops has remained uneven, with the massive predominance of three countries, three crops and one trait (Table 3). In addition, there is a growing debate on the labelling of GM food.

Costs of transgenic seeds in agricultural production: the US case

Evolution of GM seed prices over the years

Because of technology fees, transgenic seeds are more expensive than conventional seeds. This higher price is reinforced by the contractual obligation not to save part of the harvest for re-sowing the following year. However, GM seeds offer access to some new crop characteristics, which explains their purchase by farmers. In the last 18 years, the majority of GM crops have been herbicide-tolerant or insect-resistant. They can enable a reduced or less expensive use of pesticides and provide some other advantages — such as time saving, ease of work, and good combination with some other techniques — as well as drawbacks — including coexistence issues with neighbouring non-GM crops and the development of weed resistance to glyphosate and insect resistance to Bt crops. These advantages and drawbacks must be assessed in each situation according to the type of trait(s) as well as the agro-climatic, socio-economic and regulatory contexts. In addition, this assessment must be made over a period of years, as the relative prices of inputs and outputs change over time (see below). Naturally, companies establish GM seed prices at levels such that their use may be profitable for farmers, at least in a large number of situations. This explains the rapid adoption of transgenic soybean, corn, and cotton in several countries. However, since their first commercial release in 1995–1996, an increase in GM seed prices has been observed. Could this increase affect the economic return and thus the rate of GMO adoption?

A detailed case study is necessary to more thoroughly assess the economic return of GM crops given GM seed price increases. The case of glyphosate-tolerant soybean has been chosen here as it is the most cultivated transgenic crop worldwide, and the US case has been chosen since USDA statistics provide unbiased data (based on random surveys) on prices and on the percentage of GM crops within each crop. For seeds, USDA statistics from 2001 provide the average prices of conventional and GM seeds paid by farmers (USDA-NASS 1992–2013). Unfortunately, USDA data on production costs do not differentiate between conventional and GM crops. Hence the margins and production costs of these two types of crops cannot be compared with public data, only the average margins and costs as well as prices of some inputs (Fig. 8).

The rate of adoption of GM soybean was rapid in the US: in 1998, 35 % of soybean area was transgenic, in 2001 68 %, in 2004 85 %, and from 2007 more than 91 % (Fernandez-Cornejo et al. 2014). In the early years, GM soybean had a single GM trait: glyphosate tolerance. In addition to saved time and ease of work, as well as good combination with conservation tillage techniques, the profitability of GM soybean lies in the seed's additional cost being compensated for by lower expenses on herbicides (Fernandez-Cornejo and Caswell 2006; Bonny 2008). Compared to conventional seeds, the premium of the transgenic ones was significant, but variable, over the period 2001–2013, ranging from 34 % to 81 %, in a non-linear fashion (58 % on average). This higher seed price has had different effects depending on the period, because of concomitant changes in the prices of related products (Fig. 9):

– During the period 1996 to 2002 when the percentage of GM soybeans was increasing rapidly, the part of seeds within operating costs doubled. However, since 1998, glyphosate prices have fallen, since the patent on this herbicide expired in the US in 2000 and a large quantity of generics was produced subsequently, except in the period 2008–2009, when some shortages occurred. Therefore, since 1998, the proportion of pesticides has decreased within total operating costs, which has compensated for the rise in the seed portion. Hence, after a high increase during the period 1996–1998, the value of the "seed+pesticide" costs within total operating costs declined during the period 1998 to 2008 (Fig. 9).

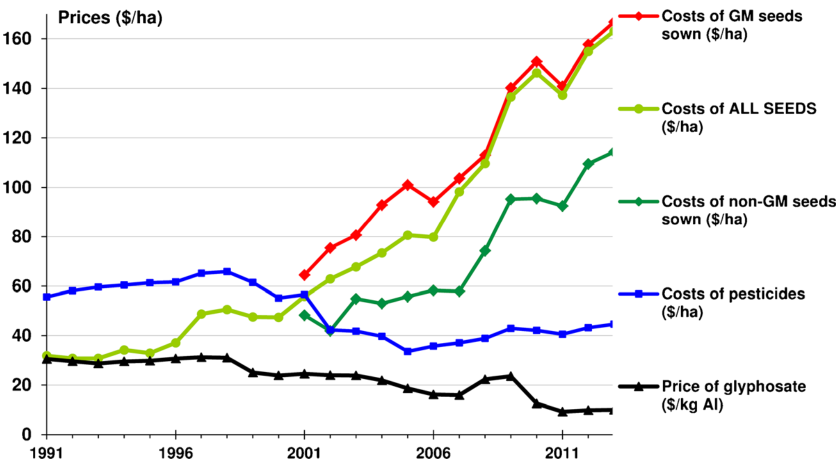

Fig. 8 Costs of GM and non-GM seeds and of pesticides in soybean production costs in the US, and price of glyphosate, 1991–2013 (author's calculation from USDA-ERS 2013a, b; USDA-NASS 1992–2013). Preliminary Data for 2013

- Over the period 2002 to 2008, the part of seeds within operating costs stabilised while the part of herbicides decreased. Thus the portion of the "seed+pesticide" costs decreased.
- After 2008, however, the part of seeds within operating costs rose again.

As for the seed cost per hectare as a percentage of gross product per ha, it also doubled over the period 1996 to 2001, and remained relatively stable from then on (Fig. 10). However, the price of conventional seed has also risen (Fig. 8). This latter trend stems notably from the increase in soybean prices at the Chicago Board of Trade (CBOT) in certain years, an increase that is reflected in both GM and non-GM seed prices, since CBOT grain prices are used as the basis for seed pricing in many contracts. Other factors may also contribute to the conventional seed price increases: in some years, farmers in the US have had difficulties in acquiring non-GM soybean seeds; and, due to demand, genetic research has also returned to some extent to the breeding of non-GM seeds, leading to a higher price for this germplasm (Milanesi 2012).

Hence, with regard to the effects of seed prices, in the first decade higher seed costs were generally compensated by reduced herbicide costs, albeit with some variation. In addition, GM soybean cultivation may also have provided some non-pecuniary benefits (Fernandez-Cornejo et al. 2014; Bonny 2008). Yet, as many GM crops have been glyphosate-tolerant, the extended use of glyphosate without a longer crop rotation or the use of other herbicides has led to the development of weeds resistant to this herbicide due to high selection pressure (Heap 2014). Over the past few years, the spread of glyphosate-resistant weeds has required use of additional herbicides and hence entailed an increase in weedkiller costs particularly in some areas (Frisvold and Reeves 2010; Bonny 2011; Frisvold 2012, 2013; NRC 2012; Benbrook 2012). Thus, pesticide costs per ha increased again from 2005, notably in locations where glyphosate-resistant weed species are more numerous (Fig. 8). However, up until mid-2013, the part of pesticide costs within operating costs didn't increase on average, although weeding can require more time and additional operations such as a return to tillage as a weed management tool.

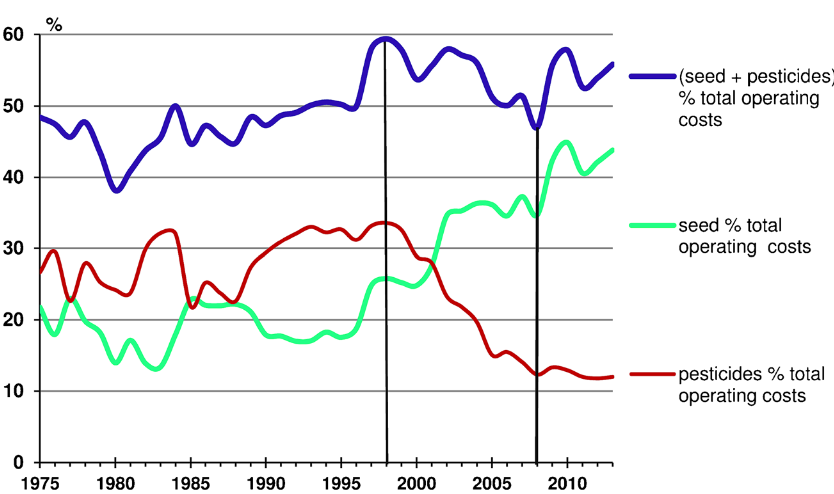

Fig. 9 Seed and pesticides in % of total operational costs of soybean (in average, US, 1975–2013) (same sources as Fig. 8). Preliminary Data for 2013

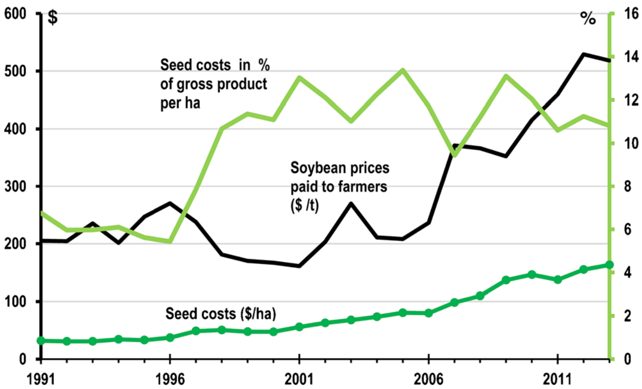

Fig. 10 Average cost of soybean seeds per ha and in % of the value of the soybean production per ha, as well as average soybean prices paid to farmers, 1991–2013 (same sources as Fig. 8). Preliminary Data for 2013. (Left scale: seed cost in $/ha and soybean prices in $/t. Right scale: seed cost in %)

Despite these factors, however, GMO adoption seems to have hardly been affected: the proportion of GM crops has not declined in the US over the past few years. The percentage of GM soybeans, GM corn and GM cotton in the total acreage of each crop is very high: in 2013, it was, respectively, 93 %, 90 %, and 90 %. If growth has been stagnant over the last few years (and further increase is scarcely possible), virtually no decrease has been noticed either. Insect-resistant cotton is the only recent exception, notably because of the development of resistance in pests (Tabashnik et al. 2013). Yet even if, either because of weed resistance or seed prices, some growers were willing to re-adopt conventional crops, this would require that sufficient conventional seed varieties were available. It may be feared that the supply of conventional varieties is much less substantial than that of GM varieties, given the predominance of GM soybean in the last fifteen years and the decrease in the number of seed companies selling conventional soybeans (Shi et al. 2009). Nevertheless, in 2010, a survey of the non-GM soybean variety pipeline found that some public and private non-GMO breeding efforts were still present (Miller-Garvin et al. 2010). A few universities and some independent breeders perform plant breeding for non-GM varieties. Indeed, in recent years, there has been an increase in the demand for non-GM food and non-GM seeds because of the rise in the organic market and the non-GM identity preserved market. Yet their proportion in the entire market remains very small: in 2011, for example, organic soybean represented 0.17 % of soybean area in the US. As the current literature does not allow a precise assessment of non-GM seed availability, further research is needed on this issue. After all, few growers have abandoned GM crops, except in specific places because of high resistance issues. If in the late 1990s the proportion of seed costs in gross product doubled with GM soybean adoption, since the early 2000s it has remained relatively stable and the higher seed costs were generally compensated by reduced herbicide costs and by the rise of soybean prices, although with some variations (Figs. 9 and 10). In addition the GM seeds have evolved.

Impacts of trait diversity and pricing, and packaging of traits

Another factor contributing to the rise of GM seed prices is the number and type of traits. GM seed companies often put new varieties with enhanced characteristics on the market. In addition, there is an increasing trend to stack several GM traits within GM seed varieties so as to simultaneously add several new characteristics (Que et al. 2010). For example, in the last ten years, an increasing proportion of GM corn in the US has included double and multiple stacked traits (as many as eight per variety), with different combinations of herbicide-tolerance, insect-resistance and (more recently) drought-tolerance (Bennett et al. 2013). Seed lifetimes have also tended to get shorter with trait stacking (Magnier et al. 2010). Although more expensive, these seeds have been adopted by many US farmers in the expectation of better performance. There is thus an increasing range of GM crop varieties. Whereas for the period 1996 to 2013, the large majority of GM crops have had only two main GM traits (Table 3), there were 45 different GM crops commercialised in March 2013 (Bennett et al. 2013), if plant species, breeding company, specific transformation event[1] and event combinations are taken into account. This large range of combinations leads to a large range of seed prices. The pricing of GM seeds differs according to the stacked events and traits, as well as by region (Shi et al. 2009, 2010, 2012; Shi and Chavas 2011; Stiegert et al. 2011). If variations in cultural practices and in soil and climate conditions are considered as well, in addition to changes from year to year, the comparative margins of conventional and transgenic crops are quite variable. In coming years the trend to multi-stack traits is likely to accelerate, contributing to higher seed prices as leading biotech seed companies seek to incorporate other traits into GM plants, such as other herbicide-tolerance or insect-resistance traits, output characteristics (such as fatty-acid composition), drought-resistance traits, etc. (see for example, Monsanto 2014; Pioneer 2014).

In 2014, the patent for Roundup Ready soybeans will expire and the glyphosate-tolerance trait will enter the public domain. As of 2015, it will be available to other companies without the need to pay royalties. Nevertheless, even if farmers are then allowed to save seeds with this glyphosate-tolerance trait, will they be able to find seeds in which this trait is not stacked with other patented traits or included in proprietary varieties? A number of specialists believe that, after

[1] "Event" in this context refers to the transformation of an organism by inserting a piece of DNA into its genome in a particular location; a single transgene incorporated in two different sites thus leads to two different events.

2014, many farmers may be led to continue to use transgenic soybean seeds in order to have access to new genetics or new traits, as the leading seed companies expect. Indeed, since the first-generation glyphosate-tolerance (GT) trait can be replaced by new GT traits, or included in varieties having other GM traits or be protected by variety patents or plant variety protection certificates, it may well be difficult to find soybean varieties with no other commercial protection (Stumo 2010; Miller 2012; Graff et al. 2012). This is already partly the case: in 2009, Monsanto put on the market a new GT soybean, the "Roundup Ready 2 Yield Soybean" (RR2) which, in addition to the glyphosate-tolerance trait, has a higher yield potential and also a higher seed price than that of the first generation of GT seeds. In 2012, this RR2 soybean was cultivated on 41 % of US soybean acreage (Monsanto 2013). The leading companies are seeking to launch other new herbicide-tolerant soybeans with stacked traits. Thus, a decrease in seed prices seems rather unlikely. However, patent expiration on biotech seed traits involves many other aspects we cannot address here (Grushkin 2013).

Conclusion

This paper aims to take stock of the contemporary GM seed industry, to provide more comprehensive data on the seed sector, and to better understand the implications of its recent and on-going evolution. In the last two decades, with the development of GM crops, a number of NGOs, media, citizens, elected officials and some farmers' associations have expressed concerns about certain trends in the seed sector, including its concentration and the increase in seed prices, which could alter seed availability, affordability, utilisation and resilience for farmers and the public as a whole. Food security depends, *inter alia*, on seed security. Seed security is usually considered in emergency situations and acute contexts (McGuire and Sperling 2011; Sperling and McGuire 2012). In fact, this concept could be more widely applied. Seed availability, access, utilisation and resilience should perhaps be considered not only at the farm level, but also within society as a whole.

As shown in the analysis, concentration in the seed sector, and particularly in the GM seed sector, is very high and likely to increase further. This concentration is reflected not only by the growing part of total seed sales commanded by the biggest seed groups, but also by the weight of these companies in R&D expenditures, GM field trials, and GM crop areas bearing their GM traits. Concentration is also reflected in the high and growing proportion of GM seeds in overall commercial seed sales, which reached almost one-third in 2013. This concentration has led to the fear that agriculture and food will soon be in the hands of a small number of transnational corporations. Another concern is that the concentration of companies may contribute to an increased focus on the most profitable or widely cultivated crops, as major firms centre their activities on the more profitable sectors, because financial markets require high returns in the seed sector comparable to other sectors. The supply of food for humanity could thereby become dependent on a handful of firms and species, whereas crops cultivated on smaller areas would become orphan sectors, with little investment in plant breeding. Breeders seek to improve seeds to obtain varieties that simultaneously present various required traits, but these required traits are numerous and change over time according to changes in context (Singh et al. 2013). Diverse species and varieties are needed because of the considerable and evolving diversity of soil and climate conditions, agro-economic situations, and end-user utilisations. Even if they are present in many countries, the few largest seed companies cannot meet the enormous range of agricultural situations and needs that exist (Access to Seeds Foundation 2014). It seems therefore to be important that public research invest in plant breeding once again, that regional SMEs can continue to provide seeds, and also that other forms of plant breeding can remain and coexist, not just GM plant breeding. The magnitude of future challenges argues for diversity in plant breeding, notably a recovery of public R&D investment in this sector and the maintenance of SMEs.

Furthermore, seed genetic value should be given a high priority; it should not be undervalued relative to technology fees, as it appears to be in GM seed prices. If plant breeding is a key domain for increasing and enhancing agricultural production, it cannot only rely upon transgenesis, today or in the future. Even if certain GM traits can be useful, the potential of genetic engineering must not be overestimated as a means of improving food security. Many other aspects and tools of plant breeding are essential, including widening the genetic diversity of crops, better adaptation to local conditions, genomics and other technologies, as well as all the many other aspects of agricultural production.

The analysis presented here has revealed strong heterogeneity in the seed sector as a whole as well as its modest economic size within the overall food chain, especially compared to downstream processing and large-scale retailing. Despite the rapid growth and significant weight of the top agbiotech companies, the influence of downstream sectors on the food chain remains dominant. Although some big seed companies have acquired many other enterprises and today represent a high share of global seed sales, the economic weight of the seed industry remains small within the food chain. The downstream sectors act powerfully upon the entire food chain, notably through their requirements and their influence on consumption patterns, as well as on agricultural and food prices.

For farmers, the profitability of transgenic crops depends on the type of GM crop, the relative prices between GM seeds and other inputs and outputs, and on certain non-pecuniary effects (saving of time, association with other practices, etc.). GM seeds may be profitable despite their additional costs if the latter are compensated by a decrease in other input costs (such as pesticides) or by a slightly higher gross profit. Herbicide-tolerant or insect-resistant crops may allow some reduction in production costs, fewer losses, and higher yields, at least in the first few years (Qaim 2009). If certain components (fatty acids, beta-carotene, etc.) can be added to the product and lead to slightly higher production prices according to final demand, GM crops with output traits may provide a slightly greater gross value. Yet the durability of these added characteristics must be considered. GM seeds can introduce some new characteristics to plants, but they must be valuable, sustainable and durable. The profitability of GM crops for farmers must not be assessed only by their direct effects within a short time-period. Follow-up study is essential given changes in prices over time as well as possible delayed spillover effects, such as the development of weed or insect resistance.

The number of new characteristics offered by GM crops is small today and has evolved little since 1996. Will more interesting traits be commercialised in the near future, and will they be widely accessible? If gene stacking makes it possible to combine several traits, it can also lead to more expensive seeds. In the countries growing GM crops, there are concerns about the rising prices of seeds in company with the trend toward gene stacking, the risk of a decrease in the supply of non-GM seeds, and the fact that the best germplasm may soon be available only in transgenic lines (Moss 2013). Because of these many consequences, gene stacking is a major issue and one that deserves greater attention.

If today there is consensus on the need for more sustainable agriculture and reinvestment in this sector, there are also strong controversies over the directions the agricultural sector should take. This controversy is especially pronounced in plant breeding: some advocate the use of modern tools of breeding, particularly those derived from biotechnology; others argue for more smallholder farming and participatory breeding, while refusing GM crops. Many people support genetic engineering because of its expected ability to confer some valuable traits more quickly, which may more efficiently address some agricultural, food, and climate issues. Others emphasise the environmental, health and socio-economic risks of GMOs, whether direct or indirect, and the fact that big agbiotech companies are subject to strong pressure from financial markets and competition for high returns, which can lead them to prioritize lucrative markets or overlook certain risks. Furthermore, the advocates of "alternatives to GMOs" emphasise the importance of seed accessibility and affordability as well as the many other aspects of agricultural production and food accessibility. To address these many current and future issues, there is no technological panacea (Royal Society 2009). Modern plant breeding methods such as biotech applications should not be opposed to agro-ecological methods, but rather should be combined with them when possible. Rejection of GMOs is often associated with the concerns expressed over the GM seed industry and its concentration. However, the seed industry is embedded in the global economic system. The direction, implementation, regulation, and practical use of genetic engineering and biotech applications depend on the governance of the seed sector. The latter depends not only on the seed sector, but also and more importantly on a better general governance of economic, social, and environmental issues.

References

Access to Seeds Foundation. (2014). *Access to seeds index. Report of the industry round table*. Haarlem: Access to Seeds Foundation.

Alston, J. M., Beddow, J. M., & Pardey, P. G. (2009). Agricultural research, productivity, and food prices in the long run. *Science, 325*, 1209–1210. doi:10.1126/science.1170451.

Altieri, M. A., & Nicholls, C. I. (2005). *Agroecology and the search for a truly sustainable agriculture*. Mexico: United Nations Environmental Programme, Environmental Training Network for Latin America and the Caribbean.

Arrow, K. J. (1962). Economic welfare and the allocation of resources for invention. In R. R. Nelson (Ed.), *The rate and direction of inventive activity: Economic and social factors* (pp. 609–625). Princeton, NJ: Princeton University Press.

Arundel, A., & Sawaya, D. (2009). Biotechnologies in agriculture and related natural resources to 2015. *OECD Journal: General Papers, Special issue Agricultural and health biotechnologies, 3*, 7–112.

Beinteima, M., & Elliot, H. (2009). *Setting meaningful investment targets in agricultural research and development: challenges, opportunities and fiscal realities. FAO, Expert Meeting on How to feed the World in 2050. 24-26/06/2009*. Rome: FAO.

Beintema, N., Stads, G.J., Fuglie, K., & Heisey, P. (2012). *ASTI Global Assessment of Agricultural R&D Spending Developing Countries Accelerate Investment*. Washington DC: IFPRI, Rome: ASTI, Rome: GFAR.

Benbrook, C. (2012). Impact of genetically engineered crops on pesticide use in the US – the first sixteen years. *Environmental Sciences Europe, 24*, 24.

Bennett, D. J., & Jennings, R. C. (Eds.). (2013). *Successful agricultural innovation in emerging economies: new genetic technologies for global food production*. New York: Cambridge University Press.

Bennett, A.B.., Chi-Ham, C., Barrows, G., Sexton, S., Zilberman, D. (2013). Agricultural Biotechnology: Economics, Environment, Ethics, and the Future. *Annual Review of Environment and Resources,* 38, doi:10.1146/annurev-environ-050912-124612

BioPlan Associates. (2013). *10 th annual report and survey of biopharmaceutical manufacturing capacity and production*. Rockville, MD: BioPlan Associates.

Black, M., Bewley, J. D., & Halmer, P. (Eds.). (2006). *The encyclopedia of seeds: Science, technology and uses*. Wallingford: CABI.

Blakeney, M. (2009). *Intellectual property rights and food security.* Wallingford: CABI.

Bonny, S. (2006). What is the future for farming inside the agri-food chain? In H. Langeveld & N. Röling (Eds.), *Changing European farming systems for a better future. New visions for rural areas* (pp. 217–222). Wageningen: Wageningen Academic Publishers.

Bonny, S. (2008). Genetically modified glyphosate-tolerant soybean in the US: adoption factors, impacts and prospects. *Agronomy for Sustainable Development, 28*, 21–32.

Bonny, S. (2011). Herbicide-tolerant transgenic soybean over 15 years of cultivation: pesticide use, weed resistance, and some economic issues. The case of the USA. *Sustainability, 3*(9), 1302–1322. doi: 10.3390/su3091302.

Bruins, M. (2008). *Biotech crops. Challenges and consequences for the seed industry.* Communication at the 8th Eastern European Seed Network meeting, Siofok, Hongrie, 16-18/11/2008.

Bruins, M. (2010). *Present and future of the seed industry.* Communication at ANPROS (Asociación Nacional de Productores de Semillas), Chile, April.

Bruins, M. (2013). *Seed Science and the Seed Industry in the 21st Century.* Communication at the Seed and Biosafety Symposium. Ames, IA, Iowa State University, 24/04/2013.

CESE (Conseil économique, social et environnemental). (2009). *Semences et recherche : Des voies du progrès*. Paris: Journaux officiels.

Context Network. (2012). *Global seed market database 2012*. West Des Moines (Iowa): Context.

Convent, B. (2003). *Seed Market: analysis and perspectives*. Presentation to the Brainstorm meeting to articulate "2025: A European Vision for Plant Genomics and Biotechnology" held in Genval, Belgium.

Cordiner, J. L. (2004). Challenges for the PSE (Process Systems Engineering) community in formulations. *Computers and Chemical Engineering, 29*, 83–92.

Day-Rubenstein, K. (2010). *Agricultural research funding in the public and private sectors*. Washington DC: USDA-ERS. http://www.ers.usda.gov/data-products/agricultural-research-funding-in-the-public-and-private-sectors.aspx.

Devgen. (2012). *Annual brochure 2011*. Ghent: Devgen.

Domina, D. A., & Taylor, C. R. (2009). The debilitating effects of concentration in markets affecting agriculture. *Drake Journal of Agricultural Law, 15*(1), 61–108.

ETC. (2008). *Who owns nature? Corporate power and the final frontier in the commodification of life*. Ottawa: ETC.

ETC. (2011). *Who will control the Green Economy?* Ottawa: ETC.

ETC. (2013a). *Gene giants seek "philanthrogopoly"*. Ottawa: ETC.

ETC. (2013b). *Putting the cartel before the horse…and farm, seeds, soil and peasants etc.: Who will control the agricultural inputs?* Ottawa: ETC. ETC communiqué (111).

ETC (action group on Erosion, Technology and Concentration). (2005). *Global seed industry concentration*. Ottawa: ETC. Communiqué, Sept-Oct.

FAO. (2004). *State of food and agriculture 2003–2004 agricultural biotechnology, meeting the needs of the poor?* Rome: FAO.

Fedoroff, N. V., et al. (2010). Radically rethinking agriculture for the 21st century. *Science, 327*(5967), 833–834. doi:10.1126/science.1186834.

Fernandez-Cornejo, J. (2004). *The Seed Industry in U.S. Agriculture: An Exploration of Data and Information on Crop Seed Markets, Regulation, Industry Structure, and Research and Development*. USDA-ERS, Agriculture Information Bulletin, (786).

Fernandez-Cornejo, J., & Caswell, M. (2006). *The first decade of genetically engineered crops in the United States*. Washington DC: USDA-ERS.

Fernandez-Cornejo, J., Wechsler, S., Livingston, M., & Mitchell, L. (2014). *Genetically engineered crops in the United States*. Washington DC: USDA- ERS.

Forbes (2012–2013). Special Report. The World's Biggest Companies. The Global 2000. *Forbes*.

Freese, B. (2007). *Cotton concentration report: An assessment of Monsanto's proposed acquisition of delta and pine land.* Washington DC: International Center for Technology Assessment, Center for Food Safety.

Frisvold, G. B. (2012). *A social science perspective on weed management practices in national summit on strategies to manage herbicide-resistant weeds: Proceedings of a symposium*. Washington, DC: National Academies Press.

Frisvold, G.B. (2013). *Growing herbicide resistant crops sustainably: what farmers are (and are not) doing.* 17th ICABR Conference "Innovation and policy for the bioeconomy", Ravello (Italy), 18-21/06/2013.

Frisvold, G. B., & Reeves, J. M. (2010). Resistance management and sustainable use of agricultural biotechnology. *AgBioforum, 13*, 343–359.

Fuglie, K. O., & Toole, A. A. (2014). The evolving institutional structure of public and private agricultural research. *American Journal of Agricultural Economics*. doi:10.1093/ajae/aat107.

Fuglie, K. O., Heisey, P. W., King, J. L., Pray, C. E., Day-Rubenstein, K., Schimmelpfennig, D., et al. (2011). *Research investments and market structure in the food processing, agricultural input, and biofuel industries worldwide. ERR-130*. Washington DC: USDA-ERS.

Fuglie, K., Heisey, P. W., King, J. L., Pray, C. E., & Schimmelpfennig, D. (2012a). The contribution of private industry to agricultural innovation. *Science, 338*(6110), 1031–1032. doi:10.1126/science.1226294.

Fuglie, K., King, J., Heisey, P.W., & Schimmelpfennig, D. (2012b). Rising Concentration in Agricultural Input Industries Influences New Farm Technologies. *Amber Waves,* USDA-ERS, December.

Gallais, A. (2011). *Méthodes de création de variétés en amélioration des plantes*. Paris: Quae.

GNIS. (1982–2013). *Statistique annuelle semences et plants*. Paris: GNIS (Groupement National Interprofessionnel des Semences et plants).

Graff, G., Szczerba, M., Chi-Ham, C., & Bennett, A. (2012). *The Emergence of Agbiogenerics: implications for the future of crop genetic development*. Nashville (TN): Annual Agricultural Law Symposium.

Graziano Ceddia, M., & Rodríguez Cerezo, E. (2008). *A descriptive analysis of conventional, organic and GM crop and certified seed production in the EU*. Seville: European Commission, Joint Research Centre, Institute for Prospective Technological Studies.

Grushkin, D. (2013). Threat to global GM soybean access as patent nears expiry. *Nature Biotechnology, 31*, 10–11. doi:10.1038/nbt0113-10c.

Halsall, M. (2013). Growth in global seed markets. *Germination, 17*(4), 4–8.

Heap, I. (2014). *International survey of herbicide-resistant weeds*. www.weedscience.org

Howard, P. H. (2009). Visualizing consolidation in the global seed industry: 1996–2008. *Sustainability, 1*, 1266–1287. doi:10.3390/su1041266.

Huang, J., et al. (2005). Insect-resistant GM rice in farmers' fields: assessing productivity and health effects in China. *Science, 308*(5722), 688–690. doi:10.1126/science.1108972.

Hubbard, C. (2009). *Out of hand: farmers face the consequences of a consolidated seed industry.* Stoughton, WI: Farmer to Farmer Campaign on Genetic Engineering. http://farmertofarmercampaign.com/.

IAASTD (2008). *Agriculture at a Crossroads: International Assessment of Agricultural Knowledge, Science and Technology for Development.* IAASTD, Global Report. http://www.globalagriculture.org/

ISF (International Seed Federation). (2012). *Estimated value of the domestic seed market in selected countries*. Nyon (Switzerland): ISF. http://www.worldseed.org/isf/seed_statistics.html.

Jacobsen, S. E., et al. (2013). Feeding the world: genetically modified crops versus agricultural biodiversity. *Agronomy for Sustainable Development*. doi:10.1007/s13593-013-0138-9.

James, C. (1997). *Progressing public-private sector partnerships in international agricultural research and development*. Ithaca, NY: ISAAA (International Service for the Acquisition of Agri-biotech Applications). Briefs 4.

James, C. (2003). *Global review of commercialized transgenic crops: 2002. Feature: Bt maize*. Ithaca, NY: ISAAA. ISAAA Briefs 29.

James, C. (2013). *Global status of commercialized biotech/GM crops: 2013*. Ithaca, NY: ISAAA. ISAAA Brief 46.

Joly, B. (2012). Innovation "responsable" et développement durable. Produire la légitimité des OGM et de leur monde. *Futuribles, 383*, 89–109.

Jones, J. D. (2011). Why genetically modified crops? Philosophical transactions of the royal society A: Mathematical. *Physical and Engineering Sciences, 369*(1942), 1807–1816. doi:10.1098/rsta.2010.0345.

Jones, E. (2012). *Innovative crop protection. Communication at the greening partnership day*. Brussels: European Parliament.

Kalaitzandonakes, N., Magnier, A., & Miller, D. (2010). A worrisome crop? Is there market power in the U.S. seed industry? *Regulation, 2010–2011*, 20–26.

King, J., Toole, A., & Fuglie, K. (2012). *The complementary roles of the public and private sectors in U.S. agricultural research and development*. Washington DC: USDA-ERS. Economic Brief 9.

Le Buanec, B. (2008). Evolution of the seed industry during the past 40 years. *SEED News, The international seed magazine,* 12(4).

Le Buanec, B. (2009). *Economic importance. Current situation and expected future of internal and global markets of seed and propagating material*. Presentation at the European Conference on ensuring seed availability, European Commission, DG for Health and Consumers, Brussels, 18/03/2009. http://ec.europa.eu/food/plant/plant_propagation_material/review_eu_rules/.

Lemarié, S. (2003). Evolution des structures industrielles et de la concurrence dans les secteurs des semences et des pesticides. *Economie Rurale, 277–278*, 167–182.

Magnier, A., Kalaitzandonakes, N., & Miller, D. J. (2010). Product life cycles and innovation in the US seed corn industry. *International Food And Agribusiness Management Review, 13*(3), 17–36.

Mammana, I. (2014). *Concentration of market power in the EU seed market*. Brussels: The Greens/Efa Group in The European Parliament.

Marketline. (2013). *Global food retail*. London: Marketline.

McDougall, P. (2011). *The cost and time involved in the discovery, development and authorization of a new plant biotechnology derived trait. A consultancy study for CropLife International*. Midlothian (UK): Phillips McDougall.

McDougall, P. (2012). *The global seed market. Phillips McDougall crop protection and biotechnology consultants*. Midlothian (UK): Phillips McDougall.

McDougall, P. (2013). *R&D trends for chemical crop protection products and the position of the European Market. A consultancy study undertaken for ECPA (European crop protection Association)*. Midlothian (UK): Phillips McDougall.

McGuire, S., & Sperling, L. (2011). The links between food security and seed security: facts and fiction that guide response. *Development in Practice, 21*(4–5), 493–508. doi:10.1080/09614524.2011.562485.

McNabb, J. (2013). Sizing Up the Seed Sector. *SeedWorld,* September, 4–8.

Milanesi, J. (2012). Current and future availability of non-genetically modified soybean seeds in the USA, Brazil and Argentina. In Y. Bertheau (Ed.), *Genetically modified and non-genetically modified food supply chains: Co-existence and traceability.* Oxford: Wiley-Blackwell. doi:10.1002/9781118373781.ch7.

Miller, P. (2012) What Does the Future Hold? Seed Technology. Presentation at the 119th Annual Convention of the Grain and Feed Association of Illinois, Schaumburg, Illinois, Feb.

Miller-Garvin, J., Orf, J. H., & Naeve, S. L. (2010). *2010 Analysis of the U.S. Non-GMO Food Soybean Variety Pipeline.* US Soybean Export Council, 2nd Soyfood Alliance Meeting, 1/07/2010, Tokyo.

Moeller, N. I., & Stannard, C. (2013). *Identifying benefit flows. Studies on the potential monetary and non-monetary benefits arising from the international treaty on plant genetic resources for food and agriculture*. Rome: FAO.

Monsanto. (2013). *Supplemental information for investors*. St. Louis, MO: Monsanto.

Monsanto. (2014). *Annual R&D pipeline review. R&D pipeline resources*. St. Louis, MO: Monsanto.

Moschini, G. (2010). Competition in the US Seed Industry and the Role of Intellectual Property. *Choices Magazine*, 25(2), 1–12.

Moss, D. L. (2013). Competition, intellectual property rights, and transgenic seed. *South Dakota Law Review, 58*(3), 543–559.

Murphy, D. J. (2007). *People plants and genes. The story of crops and humanity*. Oxford: Oxford University Press.

NRC (National Research Council). (2012). *National summit on strategies to manage herbicide-resistant weeds: Proceedings of a symposium*. Washington DC: National Academies Press.

OCM (Organization for Competitive Markets). (2008). *Seed concentration articles*. Lincoln, NE: OCM.

OECD. (2009). *The Bioeconomy to 2030. Designing a policy agenda*. Paris: OECD.

OECD. (2013). *OECD seed schemes rules and regulations. OECD schemes for the varietal certification or the control of seed moving in international trade*. Paris: OECD.

Pingali, P., & Raney, T. (2005). Globalization and agricultural biotechnology research: Implications for developing countries. In R. Tuberosa, R. L. Phillips, & M. Gale (Eds.), *In the wake of the Double Helix: From the green to the gene revolution* (pp. 635–654). Bologna: Avenue Media.

Pioneer. (2014). *Research and development pipeline*. Johnston, IA: Pioneer. http://www.pioneer.com/home/site/about/research/pipeline/.

Qaim, M. (2009). The economics of genetically modified crops. *Annual Review of Resource Economics, 1*, 665–694. doi:10.1146/annurev.resource.050708.144203.

Que, Q., Chilton, M. D., de Fontes, C. M., He, C., Nuccio, M., Zhu, T., et al. (2010). Trait stacking in transgenic crops: challenges and opportunities. *GM Crops, 1*(4), 220–229. doi:10.4161/gmcr.1.4.13439.

Rabobank. (1994). *The world seed market: Developments and strategy.* Wageningen: LEI-DLO (Agricultural Economic Institute) and Rabobank.

Ragonnaud, G. (2013). *The EU seed and plant reproductive material market in perspective: A focus on companies and market shares*. Brussels: European Parliament, Policy Department B.

Research and Markets. (2013). *Seeds market by type, seed trait & geography - global trends & forecast to 2018*. Dublin: Research and Markets.

Royal Society. (2009). *Reaping the benefits: science and the sustainable intensification of global agriculture*. London: The Royal Society.

Schafer, S (2012). Behind the Seed Scene. *Farm Journal*, *Seed Guide 2012*, 28/07/2012.

Schenkelaars, P., de Vriend, H., & Kalaitzandonakes, N. (2011). *Drivers of consolidation in the seed industry and its consequences for innovation. Report for COGEM (Commissie Genetische Modificatie)*. Wageningen (NL): Schenkelaars Biotechnology Consultancy.

Science (2010). Special Issue on Food Security. *Science*, (5967), 12/02/2010, 797–834.

Shi, G., & Chavas, J. P. (2011). The effects of vertical organization on the pricing of differentiated products. *Journal of Agricultural and Resource Economics, 36*(3), 448–464.

Shi, G., Chavas, J. P., & Stiegert, K. (2009). Pricing of Herbicide-tolerant soybean seeds: a market-structure approach. *AgBioforum, 12*(3–4), 326–333.

Shi, G., Chavas, J. P., & Stiegert, K. (2010). An analysis of the pricing of traits in the US corn seed market. *American Journal of Agricultural Economics, 92*(5), 1324–1338.

Shi, G., Chavas, J. P., Stiegert, K., & Meng, X. (2012). An analysis of bundle pricing: the case of biotech seeds. *Agricultural Economics, 43*(s1), 125–139.

Shiva, V., Barker, D., & Lockhart, C. (2011). *The GMO emperor has no clothes*. New Delhi: Navdanya International.

Shiva, V., Shroff, R., & Lockhart, C. (2012). *Seed freedom a global citizens' report*. New Delhi: Navdanya International.

Singh, R. P., Prasad, P. V., & Reddy, K. R. (2013). Impacts of changing climate and climate variability on seed production and seed industry. *Advances in Agronomy, 118*, 49–110.

Smolders, W. (2005). *Commercial practice in the use of plant genetic resources for food and agriculture*. Background paper for the FAO, Commission on Genetic Resources for Food and Agriculture acting as interim committee for the International Treaty on Plant Genetic Resources for Food and Agriculture.

Sperling, L., & McGuire, S. (2012). Fatal gaps in seed security strategy. *Food Security, 4*(4), 569–579.

Spring, U. O. (2011). Genetically modified organisms: A threat for food security and risk for food sovereignty and survival. In H. G. Brauch et al. (Eds.), *Coping with global environmental change, disasters and security* (pp. 1019–1041). Berlin, Heidelberg: Springer.

Stiegert, K. W., Shi, G., & Chavas, J. P. (2011). Spatial pricing of genetically modified hybrid corn seeds. In C. A. Carter, G. Moschini, & I. Sheldon (Eds.), *Genetically modified food and global welfare* (pp. 149–171). Bingley: Emerald Group Publishing Limited.

Stumo, M. (2010). Anticompetitive tactics in Ag biotech could stifle entrance of generic traits. *Drake Journal of Agricultural Law, 15*(1), 137–148.

Supermarket News (2013). *Top 25 Global Food Retailers 2012*.

Tabashnik, B. E., Brévault, T., & Carrière, Y. (2013). Insect resistance to Bt crops: lessons from the first billion acres. *Nature Biotechnology, 31*(6), 510–521.

Tansey, G., & Rajotte, T. (Eds.). (2008). *The future control of food. A guide to International Negotiations and Rules on Intellectual Property, Biodiversity and Food Security*. London: Earthscan.

Then, C., & Tippe, R. (2009). *The future of seeds and food under the growing threat of patents and market concentration*. Lausanne: Berne Declaration.

UNCTAD. (2006). *Tracking the trend towards market concentration: the case of the agricultural input industry*. Geneva: UNCTAD (United Nations Conference on Trade and Development).

USDA-ERS (2013a). *Adoption of Genetically Engineered Crops in the U.S.* Data sets, USDA-ERS. http://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us.aspx

USDA-ERS (2013b). *Commodity Costs and Returns*, USDA-ERS http://www.ers.usda.gov/data-products/commodity-costs-and-returns.aspx

USDA-ERS (2013c). *Agricultural Resource Management Survey (ARMS), Crop Production Practices*. http://www.ers.usda.gov/data-products/arms-farm-financial-and-crop-production-practices.aspx

USDA-NASS (1992 to 2013*). Agricultural Prices*, Annual April publication from USDA National Agricultural Statistics Service. Washington DC: USDA.

van Beuzekom, B., & Arundel, A. (2009). *OECD biotechnology statistics*. Paris: OECD.

von Braun, J. (2008). The International Food Policy Research Institute on the World Food Situation. *Population and Development Review, 34*, 373–380. doi:10.1111/j.1728-4457.2008.00225.x.

von Braun, J., & Diaz, B. E. (Eds.). (2008). *Globalization of food and agriculture and the poor*. New Delhi: Oxford University Press.

von Broock, R., & Bruins, M. (2012). *Stand und Entwicklung der Firmenstruktur und der Zuchtprogramme*. Presentation at the conference Zukunft der Pflanzenzüchtung, Bern, BLW, 14/11/2012

Weasel, L. H. (2008). *Food fray: Inside the controversy over genetically modified food*. New York: Amacom.

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